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The KTeV Pure CsI Calorimeter

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THE KTeV PURE CsI CALORIMETER

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ABSTRACT

KTeV is currently building a state-of-the-art pure CsI electromagnetic calorimeter with a sophisticated digital readout. The CsI array is expected to have better than 1% resolution over a dynamic range of 2 - 64 GeV. The design of the CsI array is driven by the difficult physics goal of attempting to measure the CP violation parameter $\mathrm{Re}(\epsilon'/\epsilon)$ to 1 part in 10000 in a high-rate neutral beam environment. The physics requirements and their impact on the final design will be discussed.

1. Introduction

In spite of the fact that kaon physics is a very mature field, it remains an area of intense study at laboratories around the world. The continuing interest in kaon physics is due to the fact that the system lends itself to incisive experiments yielding results with definitive physics interpretations and because of the ever-present possibility of new discoveries. The origin of CP violation is still a subject of intense interest. Insight into this issue can be obtained by measuring the quantity $\mathrm{Re}(\epsilon'/\epsilon)$ which parameterizes CP nonconservation in $K^{\circ} \rightarrow \pi\pi$ decays. A nonzero value of ϵ' would provide definitive evidence for the presence of *direct* CP violation and would support the Standard Model interpretation of CP violation arising from a non-zero phase in the CKM matrix. A value of zero for ϵ' would be ambiguous, however, and could support either *Superweak* [1] models or the CKM model where ϵ' is equal to zero because of an accidental phase cancellation. The latter could occur for a top quark mass in the range of 200-300 GeV [2].

The most recent results on ϵ'/ϵ come from Fermilab experiment E731[3], which has obtained a result consistent with zero, and CERN experiment NA31[4], which has obtained a positive result 3σ away from zero. This is a clear discrepancy which has resulted in new, more accurate experiments being mounted at both locations.

The KTeV (Kaons at the TeVatron) collaboration at Fermilab* is presently constructing a new detector to begin operation at the beginning of 1996. The state-of-the-art detector, along with a new beamline producing intense fluxes of high-energy kaon decays, will extract the CP violating parameter $\mathrm{Re}(\epsilon'/\epsilon)$ with an accuracy of 1×10^{-4}, almost an order of magnitude improvement over current sensitivity. Additionally, the detector will be sensitive to rare K_L decays with branching ratios as small as 10^{-11}, two orders of magnitude more sensitive than current limits.

*Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin

2. Design Considerations for the KTeV Electromagnetic Calorimeter

2.1. Resolution and light output

The value of Re(ϵ'/ϵ) can be determined by measuring the double ratio of decay rates

$$\frac{\Gamma(K_L \rightarrow \pi^\circ\pi^\circ)/\Gamma(K_S \rightarrow \pi^\circ\pi^\circ)}{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)} = 1 - 6Re(\epsilon'/\epsilon). \quad (1)$$

The electromagnetic calorimeter must accurately identify and count the number of neutral kaon decays to $\pi^\circ\pi^\circ$ while controlling systematic uncertainties. The most important contribution to systematic errors which are relevant to the calorimeter are the semileptonic background due to residual $\pi e\nu$ decays where the electron is misidentified as a pion; $3\pi^\circ$ background where two photons are lost in the detector or fuse in the calorimeter; accidental activity which can cause biases which might differ for K_L and K_S events; and finally, energy scale uncertainties which can bias the event count because of the close relationship between reconstructed vertex position and cluster energies.

The calorimeter performance specifications required in order to measure ϵ'/ϵ to an accuracy of 10^{-4} have been determined largely from experience with the E731 lead glass calorimeter where electromagnetic calorimetry limitations which contribute to the systematic errors listed above have been thoroughly understood. Improved electron resolution and π-e rejection will reduce the contribution of residual semileptonic decays. Improved photon energy and position resolution will reduce backgrounds from $3\pi^\circ$ events by allowing for tighter mass cuts and by providing more efficient identification of overlapping clusters. Good shower containment and light transmission will reduce the difference in response between photons and electrons which is one of the ingredients necessary to fully understand one's absolute energy scale.

To accomplish these goals an energy resolution of 1% and a position resolution of 1 mm at the mean photon energy of 15 GeV is required. Non-Gaussian tails can spoil good energy resolution, so a line shape as nearly Gaussian as possible is required. The energy response of the calorimeter must be linear, i.e. $E_{true} = E_{meas}^{(1-\alpha)}$ where $\alpha < 0.5\%$. Finally, the components near the beam holes must be radiation hard to 10 kRads.

Pure Cesium Iodide (CsI) crystals were chosen to replace the old lead glass blocks for the KTeV project. CsI was chosen because of its light output, speed, radiation hardness, transparency and cost. Additionally, large quantities of CsI (doped with thallium) have been grown in the recent past, providing an existence proof that large scale manufacturing was possible. The calorimeter is shown in Figure 1 and the basic properties of Pure CsI can be found in the literature [5].

The calorimeter consists of 3100 pure CsI crystals, each 50 cm (27 $X_\circ$) long and read out with a Hamamatsu PMT at one end. The crystals come in two transverse sizes; 25 mm $\times$ 25 mm (small) and 50 mm $\times$ 50 mm (large). The large crystals are a cost cutting measure to reduce the number of channels. The position of the boundary between large and small crystals (0.6 m from the center of the array) was determined from the K° mass resolution as a function of the extent of the small block region.

The 50 cm length of the crystals has provided a significant challenge to the three vendors producing the crystals; Bicron, Crismatec and Horiba. Horiba has devised a process which results in single 50 cm long crystals of high quality and uniform properties along the crystal length. Bicron and Crismatec, unable to grow such long crystals, provide high quality glued pairs.

The design parameters of the CsI array were arrived at only after extensive prototyping and Monte Carlo studies using GEANT. The energy resolution of the array is found to depend primarily on shower leakage, uniformity of light output along the length of the crystals and the thickness of the material in which the crystals are wrapped. A crystal length of 50 cm (27 X_o) was chosen to minimize tails in the energy distribution due to leakage out the back of the crystal. For 20 X_o crystals, even 16 GeV showers were found to develop significant low-side tails. At 25 X_o the tails are still present, though greatly reduced. By 27 X_o the resolution as a function of crystal length begins to level out.

Because of the intrinsic longitudinal fluctuations in the development of electromagnetic showers, the calorimeter resolution degrades quickly with increasing deviations from uniform response along the crystal length. To preserve good resolution, each crystal is required to have a uniform response along its length to within 5%. Uniform response is not an intrinsic property of a 50 cm long CsI crystal. Uniformity is obtained with a compensational wrapping technique where, to first order, the half of

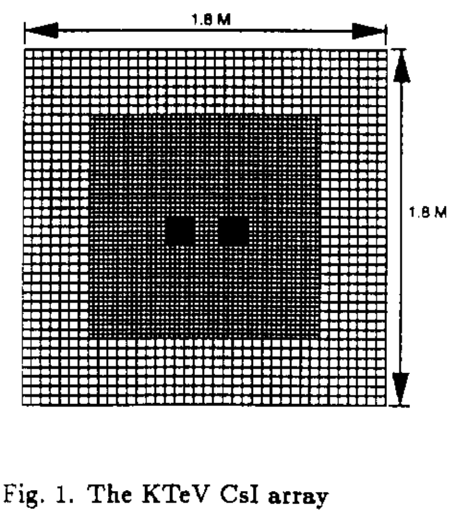

Fig. 1. The KTeV CsI array

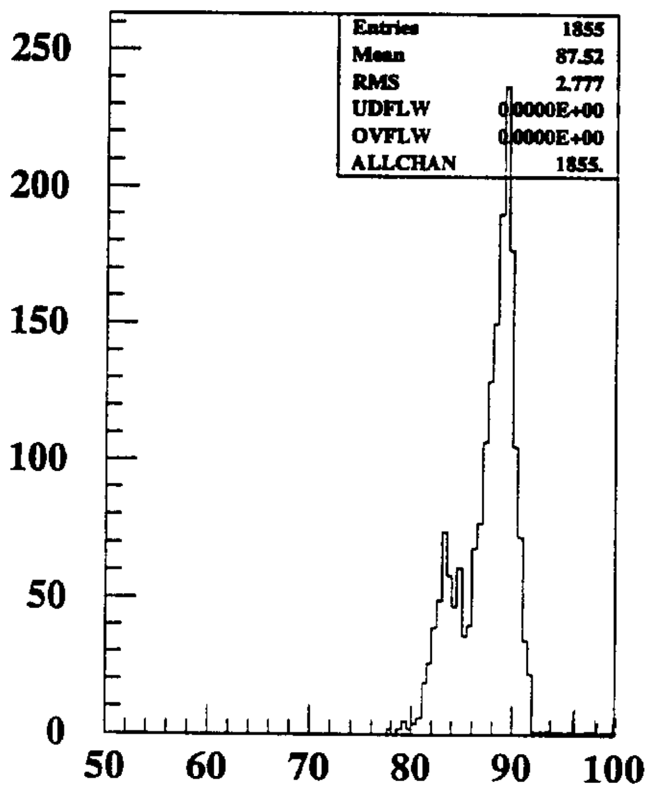

Fig. 2. Fast-to-total ratio for crystals currently in hand

the crystal farthest from the PMT is wrapped with aluminized mylar and the half closest to the PMT is wrapped in black mylar. By varying the amount of reflective material each crystal can be individually tuned. To minimize the amount of dead material between crystals, 0.005 inch thick mylar is used for wrapping.

The light output from pure CsI has both fast and slow time components with different emission spectrums[5]. Slow light is a source of accidental energy in the calorimeter and must be minimized. The crystals received from the vendors all have a fast to total (fast + slow) ratio of >70%. By placing a broad band filter (UG-11 glass), with a peak transmission of 90% at 300 nm for normally incident light and a near-zero transmission band between 400 and 650 nm, the fast-to-total ratio of the crystals can be boosted to a minimum of 80% with the peak of the distribution at 87%. The fast-to-total ratio for the crystals currently in hand, read out through filters, is shown in Figure 2.

Pure CsI has sufficient light output that photo-electron statistics will barely contribute to the overall energy resolution, even at the bottom of our dynamic range (2 GeV). The large/small crystals are read out through a 5 mm thick RTV cookie and a 1 mm thick filter into a 1.5/0.75 inch PMT resulting in an average of 30/20 p.e. per MeV. The number of p.e./MeV for both the small and large crystals currently in hand, when read out through a cookie, filter and appropriate size PMT, is shown in Figure 3.

2.2. Radiation hardness

The dominant limitation on the ability of E731 to calibrate the lead glass calorimeter was imposed by light absorption and radiation damage effects. CsI has significantly better transparency and response to radiation exposure than lead glass. Nevertheless, sufficiently large doses of radiation will degrade the transparency of CsI, reduce the overall light level and, most importantly, degrade the uniform response of the crystals over their 50 cm length. During the KTeV experiment, the crystals near the beam holes can expect an exposure of 7-10 kRads. The exposure falls off rapidly with distance from the beam. It is therefore important to identify a few hundred crystals which are radiation hard to 10 kRads and place them near the beam holes. In Figure 4 the effect of radiation damage on energy resolution is shown. The crystal was exposed to 8 kRads in several steps. At each dose level the uniformity response was measured and convoluted with longitudinally segmented GEANT showers to obtain a resolution. The GEANT showers spanned an energy range from 2 to 64 GeV. This particular crystal is relatively radiation hard, though not all of the KTeV crystals perform this well after irradiation.

CsI exhibits a wide range of susceptibility to radiation damage. Some crystals degrade significantly after 1/2 kRad while others remain unaffected after many kRads. The source of radiation damage in CsI is largely unknown. A correlation between radiation hardness and fast-to-total ratio was once suspected, but no such relationship is apparent in our data. KTeV's CsI vendors all grow large ingots from which they cut many crystals. The crystals from a given ingot tend to have similar radiation hardness properties. Ingots will be identified which have produced full length crystals which have been have been exposed to ^{60}Co and found to be radiation hard. The batches of crystals from these ingots will then be placed around the beam holes. During data taking, the uniformity of all 3100 crystals will be monitored continuously by cosmic ray muons passing transversely through the crystals and triggered by a longitudinally segmented hodoscope array above and below the calorimeter. In the event that the uniformity of a crystal degrades significantly, the reflectivity on the front face of the crystal can be increased in an attempt to boost the light collected from the half of the crystal farthest from the PMT.

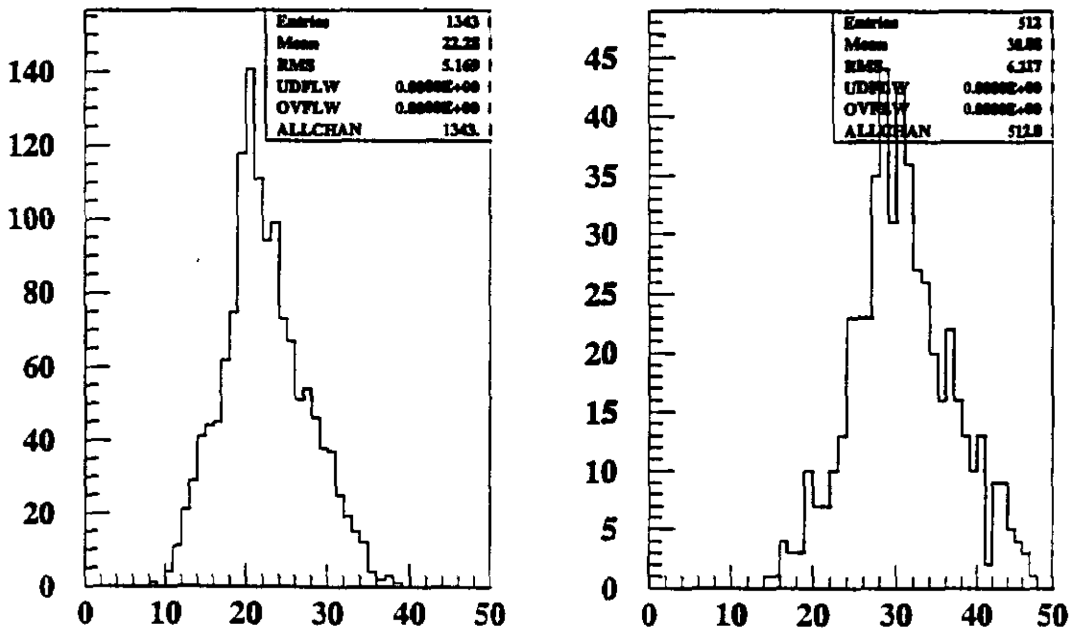

Fig. 3. Photo-electrons/MeV detected in small (left) and large (right) crystals currently in hand

3. Digital readout

A new digital readout technology has been developed at Fermilab which will be used to digitize the anode signals from the CsI PMTs at a rate of 53 MHz (the RF structure of the primary proton beam). The device resides in the base of the PMT, has 8 bits of resolution and a dynamic range of 17 bits. The device consists of an 8-bit commercial flash ADC and a custom current splitter implemented in an ASIC. The current splitter integrates binary weighted divisions of the input charge (I, I/2, I/4,...I/512), identifies the highest range which overflows and Grey codes that range as a 4-bit exponent. The integrated signal in the first non-overflowing range, or the remainder of the charge not accounted for in the exponent, is sent to the flash ADC. The 53 MHz sampling rate allows 18.8 ns slices to be recorded prior to the arrival of a CsI pulse, during the fast part of the pulse, and during the slow tail of the pulse.

The pre-samples provide a means for detecting accidental energy deposition in the calorimeter. Details of this device can be found in J. Whitmore's contribution to these proceedings.

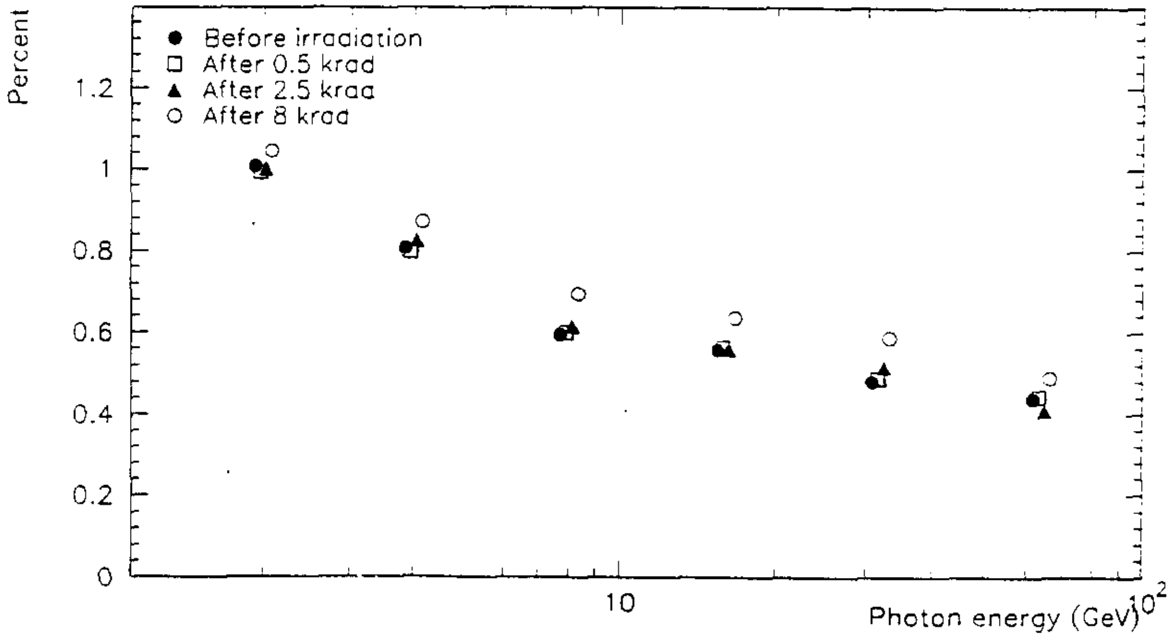

Fig. 4. Simulated energy resolution as a function of photon energy using the measured uniformity response before and after radiation exposure for a relatively radiation hard CsI crystal

4. Acknowledgements

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5. References

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